Conservative upper limits on WIMP annihilation cross section from Fermi-LAT γ-rays

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Abstract. The spectrum of an isotropic extragalactic γ-ray background (EGB) has been measured by the Fermi-LAT telescope at high latitudes. Two new models for the EGB are derived from the subtraction of unresolved point sources and extragalactic diffuse processes, which could explain from 30% to 70% of the Fermi-LAT EGB. Within the hypothesis that the two residual EGBs are entirely due to the annihilation of dark matter (DM) particles in the Galactic halo, we obtain *conservative* upper limits on their annihilation cross section $\langle\sigma v\rangle$. Severe bounds on a possible Sommerfeld enhancement of the annihilation cross section are set as well. Finally, would $\langle\sigma v\rangle$ be inversely proportional to the WIMP velocity, very severe limits are derived for the velocity-independent part of the annihilation cross section.

1. The extragalactic γ-ray background

The high latitude ($|b| > 10^o$) γ-ray emission measured by Fermi-LAT [1], given its reduced contamination by galactic sources, is a powerful tool to set limits on the contribution of DM to the measured flux. The spectrum has been obtained after the subtraction from the data of the sources resolved by the telescope, the (indeed model dependent) diffuse galactic emission, the cosmic ray (CR) background in the detector and the solar γ-ray emission. For each low–flux source there may be a large number of *unresolved* point sources which have not been detected because of selection effects, or too low emission.

Most of the unassociated high latitude sources are blazars, a class of Active Galactic Nuclei (AGNs), and they pile to the EGB with the largest flux [2]. Galactic resolved pulsars and Milli-Second Pulsars (MSPs) represent the second largest population in the Fermi-LAT catalog [3, 4] and they are expected to contribute significantly to the putative EGB. A non-negligible γ-ray flux seems to be guaranteed by unresolved normal star-forming galaxies [5]. Ultra-high energy CRs (UHECRs) may induce secondary electromagnetic cascades, originating neutrinos and γ-rays at Fermi-LAT energies [6]. Unresolved blazars and MSPs are believed to contribute at least few percent to the Fermi-LAT EGB, while predictions for star-forming galaxies and UHECRs are highly model dependent. In the following, we describe few classes of γ-ray emitters whose unresolved flux is firmly estimated in a non-negligible Fermi-LAT EGB percentage. In a conservative scenario (Model I), we will subtract AGN and MSPs to the Fermi-LAT EGB as derived in Ref. [1]. A more relaxed model (Model II) will be drawn by the further subtraction of a minimal flux from star-forming galaxies and CRs at the highest energies. The derivation of each contribution is described in details in [7].

1.1. Models for the EGB

The aim of this Section is to subtract from the Fermi-LAT EGB [1] additional contributions from unresolved sources at latitudes $|b| > 10^{\rm o}$. The contributions removed from the Fermi-LAT spectrum are minimal. In fact, the predictions that we will take into account for the relevant unresolved sources are the lowest ones according to the literature. For the Model I, we subtract from the Fermi-LAT EGB [1] the unresolved contributions for both BL Lacs and FSRQs, and MSPs. Model II for the EGB refers to the scenario where the additional contributions from star-forming galaxies and UHECRs add to explaining the Fermi-LAT EGB. For all the details, the interested reader is addressed to Ref. [7]. The ensuing fluxes are displayed in Fig. 1. At 100 MeV, Model II explains about 70% of the Fermi-LAT EGB, while above 1-2 GeV they count about 50% of the total.

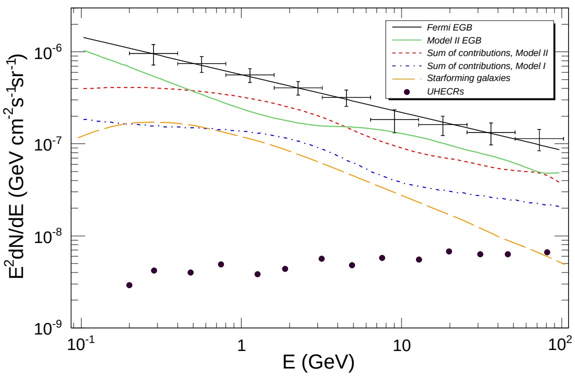

Figure 1. γ-ray spectrum for $|b| > 10^{\rm o}$ latitudes. Fermi-LAT data points are displayed along with their power–law fit (solid black curve) [1]. Dots and long dashed-curve (yellow) correspond to the UHECRs and star-forming galaxies γ-ray fluxes, respectively. Dot-dashed (blue) curve: sum of BL Lacs, FSRQs and MSPs fluxes. Short-dashed (red): sum of all the unresolved components. Solid (green) curve is derived by subtracting all the contributions to the Fermi-LAT result (Model II).

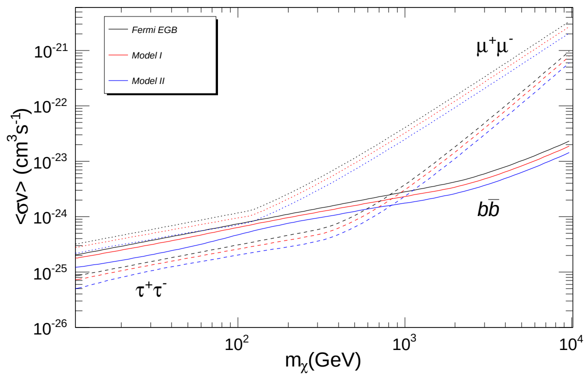

Figure 2. Upper bounds on $\langle \sigma v \rangle$ from γ-ray in the high latitude galactic halo, as a function of the DM mass. From top to bottom, solid lines refer to 90% C.L. limits from the comparison with Fermi-LAT EGB (black lines), Model I (red lines), Model II (blue lines) (see text for details). Dotted, solid and dashed lines correspond DM annihilation into $\mu^+\mu^-$, $b\bar{b}$, $\tau^+\tau^-$, respectively.

2. Upper bounds on DM annihilation cross section

We make the hypothesis that the residual fluxes in Fig. 1 are entirely provided by the γ-rays produced by thermalized WIMP DM in the halo of the Milky Way. For the prediction of the

DM flux we refer to [7], and simply remind that all the considered DM density profiles provide very similar results for latitudes well above the galactic plane. We derive upper bounds at 90% C.L. on the WIMP annihilation cross section from the γ-ray Fermi-LAT EGB and the EGB residual fluxes identified as Model I and II. They are displayed in Fig. 2 and detailed in [7]. The subtraction of the minimal amount of γ-rays from unresolved sources lowers the limits on $\langle\sigma v\rangle$ by at least 50%. Our limits are *conservative*: it is very unlikely that a higher $\langle\sigma v\rangle$ be compatible with Fermi-LAT EGB. Similarly, our upper limits could be lowered only with assumptions on non-homogeneous DM distributions or, of course, by comparing to a smaller EGB residual.

2.1. Bounds on the Sommerfeld enhancement for $\langle\sigma v\rangle$

Recent claims on the excess of CR positrons [8] have stimulated the interpretation of data in terms of annihilating DM with fairly large annihilation cross sections of the order of $10^{-23}-10^{-22}$ cm^3/s. These numbers are at least three orders of magnitude larger than the value indicated by observations of the DM abundance due to thermal production. One way to boost the annihilation cross section is through the Sommerfeld effect [9, 10, 11, 12], generically due to an attractive force acting between two particles, *i.e.* a Yukawa or a gauge interaction. In the case of DM particles, the main effect of such an attractive force would be to enhance $\langle\sigma v\rangle$ by a factor proportional to $1/\beta = c/v$, where v is the velocity of the DM particle ($1/v$ enhancement). The net result on the annihilation cross section writes as $\langle\sigma v\rangle = \mathrm{S}\ \langle\sigma v\rangle_0$, where S sizes the Sommerfeld enhancement of the annihilation amplitude. We have evaluated the Sommerfeld enhancement S using the approximation of the Yukawa potential by the Hulthen potential, for which an analytic solution is possible [13, 14] (and checked that the solution coincides with the numerical one).

In Fig. 3 we show the Sommerfeld enhanced cross sections with over-imposed the upper bounds from the residual EGB Model I and Model II (see Fig. 2). Our results show that a Sommerfeld enhancement due to a force carrier of $m_\phi < 1$ GeV (coupling $\alpha = \frac{1}{4\pi}$) is strongly excluded by Model I and II for the Fermi-LAT EGB data. For a massive force carrier (90 GeV) only the resonant peaks above the TeV mass are excluded. The result holds for $\beta = 10^{-8}$ up to $\beta = 10^{-3}$.

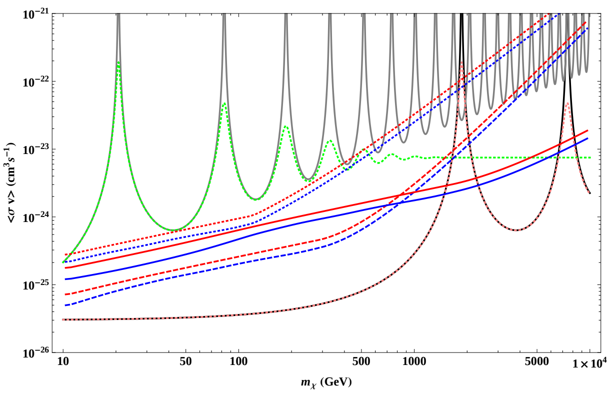

Figure 3. Sommerfeld enhanced $\langle\sigma v\rangle$ as a function of the DM mass, for $\alpha = \frac{1}{4\pi}$. Solid: $\beta = 10^{-8}$, dotted: $\beta = 10^{-3}$. The upper (lower) resonant curve is obtained for a force carrier of mass $m_\phi = 1$ GeV (90 GeV). The upper (lower) dotted, solid and dashed curves correspond to the upper bounds for EGB Model I (Model II) in $\mu^+\mu^-$, $b\bar{b}$, $\tau^+\tau^-$, respectively (see Fig. 2.)

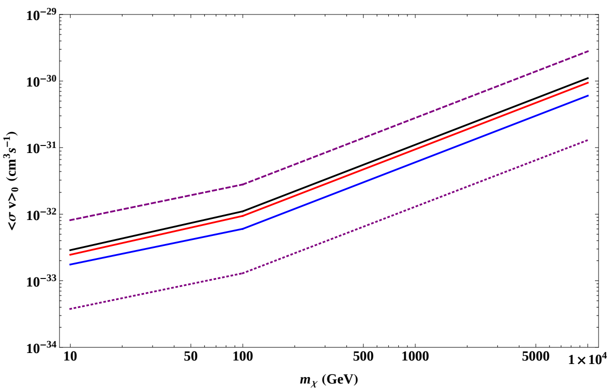

Figure 4. Bounds on $\langle\sigma v\rangle_0$ as a function of the DM mass. The central three bounds are obtained for $M_c = M_\oplus$, and from Fermi-LAT EGB (black line), Model I (red line) and Model II (blue line) respectively, from top to bottom. The upper (lower) purple lines are derived for Model II EGB and $M_c = 10^2 M_\oplus (10^{-2} M_\oplus)$.

2.2. Bounds from the high-redshift protohalos

A possible way to boost the annihilation rate is to modify the particle theory and make the ansatz that the annihilation cross section depends on the inverse of the velocity. A boosted production of γ-rays in models with $\langle\sigma v\rangle \propto 1/v$ has been proposed for the first bound objects formed in the early phases of the universe [15, 16, 7]. The velocity dispersion of the first protohalos that collapse at redshift z_C is estimated to be very small ($\beta \sim 10^{-8}$) [16]. The photons arising from WIMP annihilations in very early halos can freely propagate with their energy red-shifting and reach the Earth in the range $\sim$ keV - TeV, while photons emitted out of this transparency window are absorbed by the intergalactic medium. The $1/v$ enhancement of the annihilation cross section may be simply parameterized [16]: $\langle\sigma v\rangle = \langle\sigma v\rangle_0 \frac{c}{v}$ cm^3/s. We have evaluated the energy density in photons today from WIMP annihilation in the primordial halos and compared with the experimental photon density inferred for the Fermi-LAT, Model I and Model II EGB [1], obtained by integrating the photon flux on the Fermi-LAT energy range (100 MeV - 100 GeV) [7]. The results are displayed in Fig. 4. The bounds on $\langle\sigma v\rangle_0$ are strong: for WIMP masses below 100 GeV it is forced to be $< 10^{-33}$ cm^3/s. Upper bounds grow to $< 10^{-32}$ cm^3/s for $m_\chi \simeq 1$ TeV and sets to $< 10^{-31}$ cm^3/s at 10 TeV. We make notice that they are more stringent than limits obtained from primordial light elements abundance and CMB anisotropies [17] and significantly improve the bounds of Ref. [16].

3. Conclusions

The γ-ray EGB measured by Fermi-LAT [1] likely includes contributions from galactic and extragalactic *unresolved* sources. We have discussed two residual EGB fluxes derived by the subtraction of unresolved BL Lacs, FSRQs and galactic MSPs, star-forming galaxies and UHECRs to the γ-ray EGB measured by Fermi-LAT. From our new residual EGB fluxes, we have set upper limits on the DM annihilation cross section into γ-rays. A conservative upper bound on $\langle\sigma v\rangle$ is derived by assuming that our new residual fluxes are entirely due to WIMPs pair-annihilating in the halo of our Galaxy. Furthermore, we have shown these EGB residuals bound the Sommerfeld enhancement of $\langle\sigma v\rangle$ to a factor of 3-10-50-200 for m_χ=10-100-1000-5000 GeV, respectively. In case of a Yukawa-like potential, a force carrier heavier than 1 GeV is required. Finally, within the hypothesis that $\langle\sigma v\rangle$ is inversely proportional to the WIMP velocity, very severe limits are derived for the velocity-independent part of the annihilation cross section.

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